EFFECT OF HANDWHEEL SIZES ON THE TURNING SPEED.

BY

PAULO VIRGILIO DIDIER BARBOSA VIANA

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EFFECT OF HANDWHEEL SIZES ON THE TURNING SPEED

A Thesis

Submitted to the Faculty

of

Purdue University

by

Paulo Virgilio Didier Barbosa Viana

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18064

TABLE OF CONTENTS

Page

ABSTRACT i

INTRODUCTION 1

PURPOSE 3

EQUIPMENT AND PROCEDURE 4

RESULTS 10

CONCLUSIONS 19

APPENDIX A. COMPLETE DATA FOR ALL OPERATORS, HANDWHEELS AND TORQUES 20

APPENDIX B. STATISTICAL ANALYSIS OF RESULTS 26

APPENDIX C. APPLICATION OF LAGRANGE'S INTERPOLATION FORMULA TO ESTIMATE THE RADII OF HANDWHEELS MAXIMIZING THE TURNING SPEED 29

APPENDIX D. SAMPLE OF KYMOGRAPH PAPER 32

APPENDIX E. PHYSICAL CHARACTERISTICS OF OPERATORS 33

BIBLIOGRAPHY 34

LISTS OF FIGURES AND TABLES

List of Figures

Figure		Page
1.	The Experimental Set-up and the Kymograph......	5
2.	The Handwheels..................................	6
3.	Operators Average Time per Revolution versus Radii of Handwheels..........................	16
4.	Relationship Between Torques and Cranking Radii of Handwheels for the Condition of Maximum Turning Speed..............................	17

List of Tables

Table		Page
1.	Means and Ranges of Observed Times. Torque: 0.9 in-lb..............................	11
2.	Means and Ranges of Observed Times. Torque: 10.7 in-lb.............................	12
3.	Means and Ranges of Observed Times. Torque: 28.2 in-lb.............................	13
4.	Means and Ranges of Observed Times. Torque: 57.4 in-lb.............................	14
5.	Means and Ranges of Observed Times. Torque: 84.6 in-lb.............................	15
6.	Torque 0.9 in-lb. Complete Date for All Operators and Handwheels....................	21
7.	Torque 10.7 in-lb. Complete Date for All Operators and Handwheels....................	22
8.	Torque 28.2 in-lb. Complete Data for All Operators and Handwheels....................	23

Table Page

9. Torque 57.4 in-lb. Complete Data for All Operators and Handwheels.................. 24

10. Torque 84.6 in-lb. Complete Data for All Operators and Handwheels.................. 25

11. Physical Characteristics of Operators......... 33

ABSTRACT

The purpose of this thesis is to investigate the effect of the diameter of handwheels on the maximum speed of turning that an operator can impart to a handwheel for different torques applied to the handwheel shaft.

Five handwheels were studied ranging in cranking radii from 1.625 to 6.375 inches.

Five different torques were used ranging from 0.9 to 84.6 in-lb.

Ten subjects were tested. The subjects were volunteers from the male population of Purdue University.

Based upon the results a family of curves was drawn showing the relationship between the time per revolution and the radii of handwheels for different torques. The minima of these curves, as obtained by means of Lagrange's interpolation formula, were used to draw a graph showing the relationship between torques and radii of handwheels for the condition of maximum turning speed.

The analysis of the results led to the following conclusions:

For each individual the maximum speed of turning seems to be affected, within the range of the present experiment, by two factors: a) The muscular force required for turning the handwheel, b) The radii of the handwheel.

There is a strong indication, statistically

significant at the 1% level, that, for a given torque, one specific handwheel among those tested produces the maximum turning speed. This fact appears to justify the use of the maximum turning speed as an objective criterion for the selection of handwheels.

The curve showing the relationship between torques and radii of handwheels for the condition of maximum turning speed should provide an approximate solution for the problem of selecting that handwheel which should allow for the maximum speed for a particular torque.

EFFECT OF HANDWHEEL SIZES ON THE TURNING SPEED

INTRODUCTION

The study of the performance of machine control devices first caught the attention of investigators as early as 1926.⁽¹⁾ With the outbreak of World War II a concerted drive was made to eliminate much of the uncertainty impairing the utilization of human abilities in the operation of equipment. To this end, many investigations have been performed on control devices such as knobs, levers and handwheels.

In 1946 Raines and Rosenbloom⁽²⁾ studied the performance of handwheels operating at maximum speed and also at a moderate constant speed. In this work they arrived at a graph showing the relationship between the turning speed and the turning force required when several subjects operated at maximum speed a handwheel 1.5 inches in diameter. This graph indicates an approximate linearity between the turning speed and the turning force and also a wide variability among individuals. However, because of the wide variability among individuals, Raines and Rosenbloom felt

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(1) Kuhne, W. P., Studies Concerning the Optimum Determination of Reactions of Force on Controls of Machines, Industrielle Psychotechnick, v3, n6, p167-172, June 1926.

(2) Raines, A. and Rosenbloom, J. H., Ideal Torques for Handwheels and Knobs, Machine Design, v18, August 1946.

that it was worthless to pursue further investigation of the operation of handwheels at maximum speed. In their investigation at a moderate constant speed, they attempted to introduce a selective criterion for handwheels based on the subjective feelings of the operators.

In 1948 an extensive study was undertaken by Reed(3) on the factors influencing rotary performance. Reed's work is a step forward from that of Raines and Rosenbloom in the sense that it proves the existence of a definite relationship between the cranking radius and the maximum turning speed of handwheels. In his experiment Reed used handwheels ranging in cranking radii from 0.394 to 7.88 inches and torques ranging from zero to 4.34 in-lb.

Based upon this previous research there appears to be a need for further investigation and the introduction of a basis for an objective selection of handwheels to operate at maximum speed.

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(3) Reed, J. D., Factors Influencing Rotary Performance, The John Hopkins University, Ph.D. Dissertation, 1948.

PURPOSE

The purpose of this thesis is to investigate the effect of the cranking radii of handwheels on the maximum speed of turning that an operator can impart to the handwheel.

EQUIPMENT AND PROCEDURE

The Apparatus

The apparatus (Fig. 1) used consisted of a shaft to support the handwheel and a belt arrangement designed to permit the application of different torques to the shaft of the handwheel. The torques were set by varying the belt tension with the aid of turnbuckles, (see Fig. 1). The shaft was supported by self-aligning bearings to minimize any possible effects resulting from the deflection of the shaft under heavy belt tensions.

Five handwheels (Fig. 2) were used, with cranking radii of 1.625, 2.250, 3.062, 4.500 and 6.375 inches. These handwheels will be referred to as handwheels 1,2,3, 4 and 5, respectively.

The handwheels had fixed handles which had different shapes as can be seen from Fig. 2. Fixed handles were not desirable for the present experiment because of the variable friction between the hand of the operator and the handle of the handwheel; this difficulty was overcome by providing the operators with a cotton glove.

Five torques were used: 0.9, 10.7, 28.2, 57.4 and 84.6 inch-pounds. These were dynamic torques as estimated from the readings on the tension scales when the handwheel shaft was being turned at the maximum speed by an operator of approximately average strength. The dynamic torques

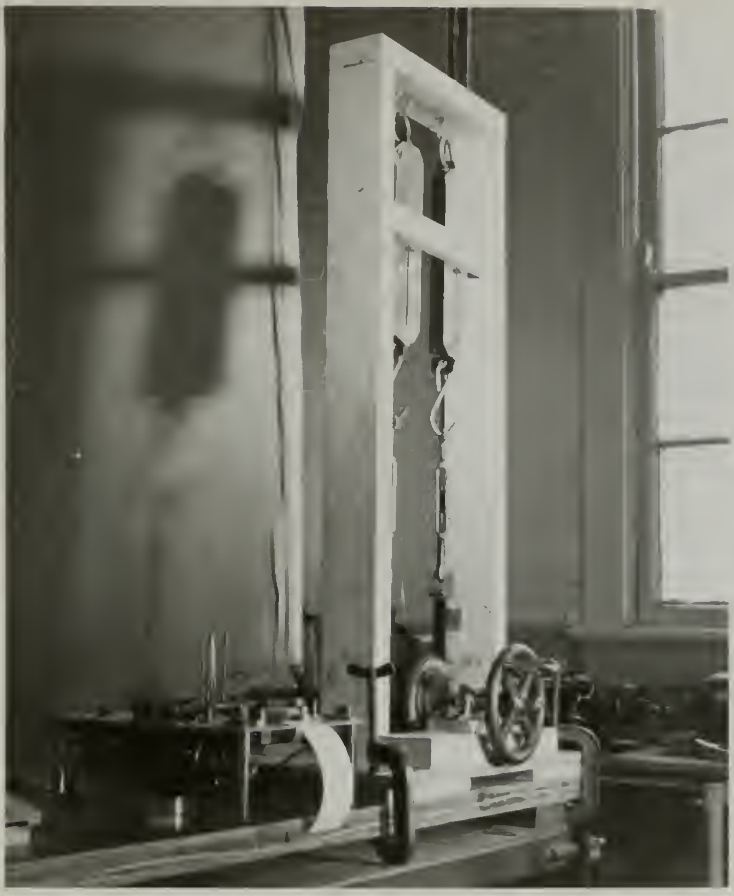

Fig. 1 THE EXPERIMENTAL SET-UP AND THE KYMOGRAPH

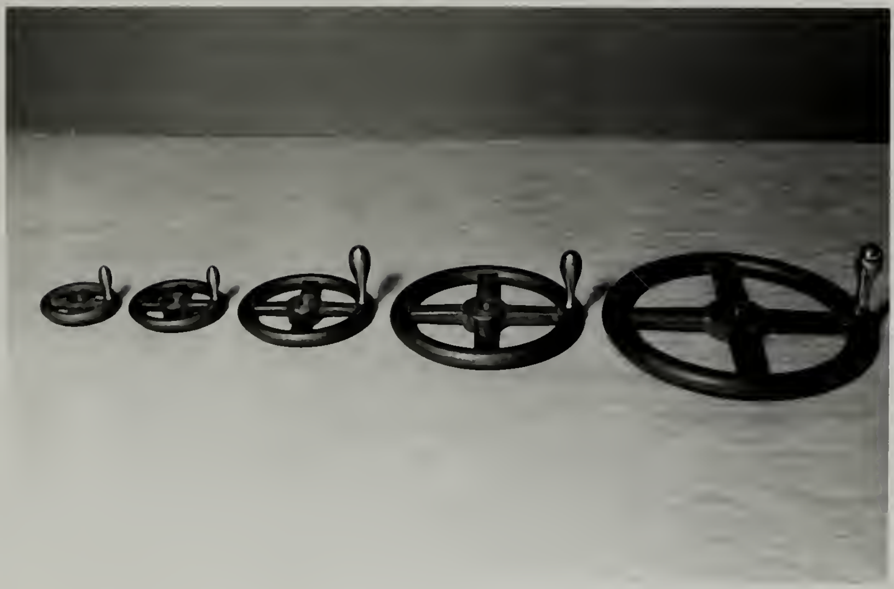

Fig. 2 THE HANDWHEELS

were found to be very close to the static torques as can be seen from the following table:

Dynamic Torques:	10.7	28.2	57.4	84.6
Static Torques:	10.1	28.2	59.0	89.0

The Timing Device

The Kymograph(4) (Fig. 1) was used to measure the speed of turning of the handwheel. In order to use this timing device a bumper was attached to the handwheel shaft in such a way that in each revolution this bumper operated a micro switch which closed the circuit for the kymograph. The time for each revolution could be measured then by the distance between each pair of pips in the kymograph paper. (See Appendix D for sample) One centimeter of kymograph paper represents 0.0436 seconds of time.

The selection of subjects

The subjects used in the experiment were volunteers from the male population of Purdue University. All were right handed and had no injuries to their hands or arms. They varied in age from 29 to 39 years with an average of 31.9 years. Their average height was 5 ft-10 in and ranged from 5 ft-8 in to 6 ft-2 in. The elbow height of the operators varied from 40.5 to 46 in with an average of 43.2 in. (For the physical characteristics of each operator, see Appendix E)

The experimental procedure

For each experiment the handwheel shaft was adjusted

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(4) For a discussion of the Kymograph, see Barnes, R.M., University of Iowa Studies, Bulletin n-6, February 1936

to be at the height of the operator's elbow because it was assumed that the elbow is the natural center of rotation for the forearm in the operation of handwheels. The operator was required to stand in front of the handwheel with the right arm and the tip of the right foot in the vertical plane containing the handwheel shaft. The tips of the feet were 15 inches apart and 8 inches away from the vertical plane containing the handwheel. Before each run the operator was instructed on how to grasp the handle and was required to perform one or two revolutions to get the feeling of that torque which was set for each run. Then, the operator was encouraged not to attempt to reach the maximum speed of turning in the first two revolutions but from then on he should apply his maximum physical exertion in order to impart the maximum speed to the handwheel. The objective of this precaution was to reduce the muscular strain usually associated with the instantaneous application of a great muscular force. Each operator performed 20 runs in which the different handwheels and torques were randomly distributed. These 20 runs, except for the randomization, followed the scheme illustrated in the table below:

Handwheels	Torques				
	0.9	10.7	28.2	57.4	84.6
1.625	1	2	3		
2.250	4	5	6		
3.062	7	8	9	10	
4.500	11	12	13	14	15
6.373	16	17	18	19	20

The reason for the blank cells in the table above is that it was found impractical to use some of the smaller handwheels for heavy torques.

The duration of each run was about 3 seconds and the interval between the runs was 3 minutes.

The Sampling Procedure

For each run, 6 observations were made of the time required to complete the revolutions from the 8th to the 13th inclusive. Therefore, for each subject 20 cells were obtained with 6 observations per cell. In all, 10 subjects were tested making a total of 200 cells with 6 observations each.

RESULTS

The data for all operators, handwheels and torques are summarized in Tables 1 to 5. The complete data from which these tables were prepared is included in Appendix A. (For the homogeneity of measurement error see Appendix B)

Using the mean time per revolution among all operators the family of curves shown in Fig. 3 was obtained. From this family of curves it can be seen that:

a) For any given size of a handwheel, the time for completion of one revolution increases as the torque increases, or, what amounts to the same thing, the speed of turning decreases as the force required for turning increases.

b) If the torque is zero, or nearly so, the time per revolution increases with the radius of the handwheel.

Tables 1 to 5 show a wide variability among individuals in their abilities to impart the maximum turning speed to a handwheel. However, they show also a strong indication that, for a given torque, one specific handwheel among those tested produces the maximum turning speed regardless of the physical strength of the operators involved. (The significance test for speeds of handwheels is presented in Appendix B) On the basis of this fact a graph was constructed (Fig. 4) relating the radii of handwheels and torques for the condition of maximum turning speed. The

Table 1

MEANS AND RANGES OF OBSERVED TIMES

TORQUE: 0.9 in-lb

	Handwheels									
	1		2		3		4		5	
Operator	R	$\bar{x}$	R	$\bar{x}$	R	$\bar{x}$	R	$\bar{x}$	R	$\bar{x}$
A	5.1	36.4	2.5	36.4	1.9	38.6	1.1	45.6	4.0	55.7
B	2.2	34.4	3.3	37.6	6.1	42.4	2.2	44.1	4.0	48.5
C	2.5	33.6	2.0	34.1	1.9	36.5	0.8	41.6	1.3	45.3
D	[illegible]	39.8	2.5	40.8	4.0	43.8	2.3	45.8	1.7	50.9
E	5.4	35.2	2.4	36.7	3.5	37.7	2.9	46.0	2.0	52.9
F	1.8	37.0	1.9	39.4	1.7	40.3	2.5	43.4	2.0	48.0
G	1.2	37.5	0.3	39.5	3.0	40.5	3.3	43.6	1.4	51.2
H	1.7	35.0	2.6	36.8	2.4	39.2	3.5	43.2	2.7	47.9
I	2.9	36.2	2.0	38.3	2.1	38.8	1.8	42.7	5.6	48.3
J	2.5	34.6	2.0	36.3	1.6	38.6	3.4	45.2	3.3	47.0
$\bar{\bar{X}}$		35.97		37.59		39.64		44.12		49.57

Table 2

MEANS AND RANGES OF OBSERVED TIMES

TORQUE: 10.7 in-lb

	Handwheels									
	1		2		3		4		5	
Operator	R	$\bar{x}$	R	$\bar{x}$	R	$\bar{x}$	R	$\bar{x}$	R	$\bar{x}$
A	3.0	41.5	2.4	41.0	3.2	41.6	2.6	46.6	3.0	56.9
B	3.9	45.6	2.8	39.7	1.8	42.6	1.6	45.0	3.4	53.4
C	4.2	39.7	3.3	37.8	1.5	37.9	4.0	42.4	3.2	48.9
D	2.2	51.5	2.0	45.0	4.0	45.8	3.8	52.6	4.2	59.8
E	2.7	46.0	2.2	38.7	3.7	40.0	6.0	46.1	2.2	54.3
F	2.6	51.2	1.8	40.0	2.4	40.6	1.2	46.5	2.7	47.2
G	4.5	49.0	2.8	43.0	2.8	43.2	2.2	44.7	0.6	53.6
H	3.7	45.4	2.6	38.9	2.6	41.4	2.7	44.5	1.6	51.0
I	1.7	46.4	3.9	41.3	1.6	42.0	2.7	43.6	0.4	51.3
J	3.1	49.8	1.1	41.2	3.0	43.6	2.8	46.5	2.5	52.6
$\bar{X}$		46.61		40.66		41.87		45.85		52.90

Table 3

MEANS AND RANGES OF OBSERVED TIMES

TORQUE: 28.2 in-lb

	Handwheels									
	1		2		3		4		5	
Operator	R	$\bar{x}$	R	$\bar{x}$	R	$\bar{x}$	R	$\bar{x}$	R	$\bar{x}$
A	5.7	56.8	3.5	46.0	4.0	45.6	1.6	49.2	2.7	57.3
B	4.9	81.4	4.7	62.3	3.1	51.6	4.6	52.6	2.8	60.4
C	4.3	54.6	3.5	47.7	2.1	42.3	2.4	44.6	3.5	49.6
D	4.1	79.0	5.3	62.5	2.4	50.6	5.3	51.7	2.7	54.4
E	2.0	59.5	9.5	49.1	3.9	46.5	2.5	48.4	2.9	55.4
F	11.5	82.0	9.6	64.8	2.0	46.9	1.1	50.0	3.0	51.6
G	6.0	77.3	3.6	57.4	2.5	46.4	2.3	48.0	2.4	54.0
H	1.8	63.6	5.8	52.5	2.0	43.6	0.5	45.7	2.2	52.5
I	4.3	76.0	2.6	62.4	0.3	43.6	1.5	46.3	3.8	56.8
J	1.7	64.2	2.9	54.2	2.3	44.3	2.0	48.5	1.5	54.9
$\bar{X}$		69.44		55.89		46.14		48.50		54.69

Table 4

MEANS AND RANGES OF OBSERVED TIMES

TORQUE: 57.4 in-lb

	Handwheels									
	1		2		3		4		5	
Operator	R	$\bar{x}$	R	$\bar{x}$	R	$\bar{x}$	R	$\bar{x}$	R	$\bar{x}$
A					5.2	59.6	4.3	52.7	5.5	57.9
B					13.2	73.7	2.8	60.5	6.1	62.6
C					4.2	51.4	2.2	49.3	1.5	51.3
D					4.2	67.7	2.4	52.4	3.0	59.7
E					5.8	62.8	2.8	54.5	2.0	59.1
F					3.8	76.2	1.7	52.4	6.2	56.2
G					3.6	64.8	2.8	56.2	3.4	60.0
H					4.0	56.6	2.3	51.7	2.1	55.8
I					3.9	67.2	4.0	55.6	1.9	62.0
J					4.0	63.8	1.7	52.4	3.7	55.8
$\bar{X}$						64.38		53.77		58.04

Table 5

MEANS AND RANGES OF OBSERVED TIMES

TORQUE: 84.6 in-lb

	Handwheels									
	1		2		3		4		5	
Operator	R	$\overline{x}$	R	$\overline{x}$	R	$\overline{x}$	R	$\overline{x}$	R	$\overline{x}$
A							5.2	64.1	3.5	61.6
B							8.4	69.7	5.0	65.8
C							3.4	53.2	3.3	51.9
D							5.9	72.5	2.4	60.4
E							4.1	62.6	6.0	62.1
F							2.0	70.8	4.2	68.9
G							2.2	65.6	1.9	62.4
H							2.6	61.2	1.8	58.1
I							2.2	70.2	2.5	64.8
J							1.9	60.8	4.1	59.8
$\overline{X}$								65.07		61.58

Fig.3

OPERATORS AVERAGE TIME PER REVOLUTION

VERSUS RADII OF HANDWHEELS

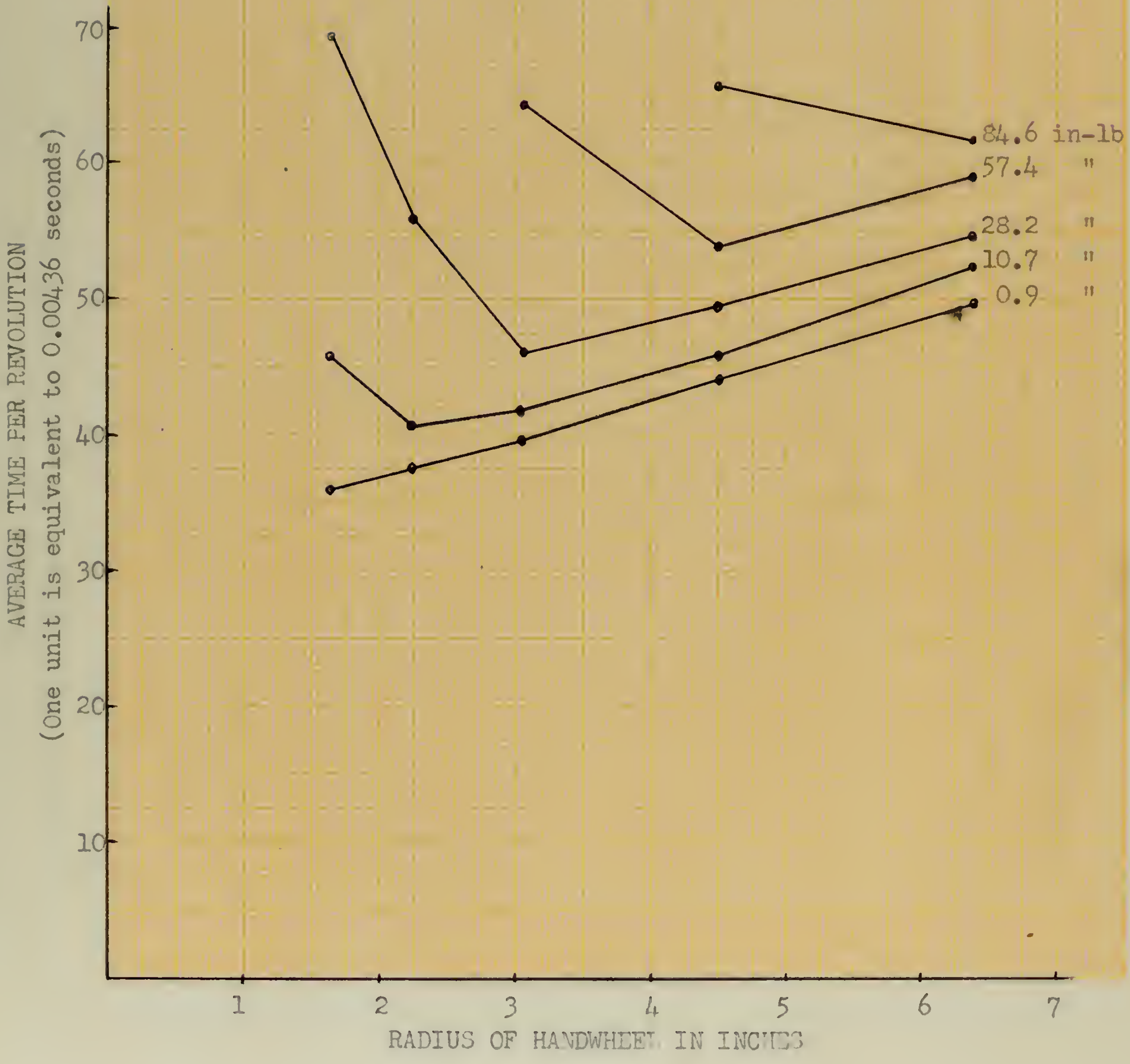
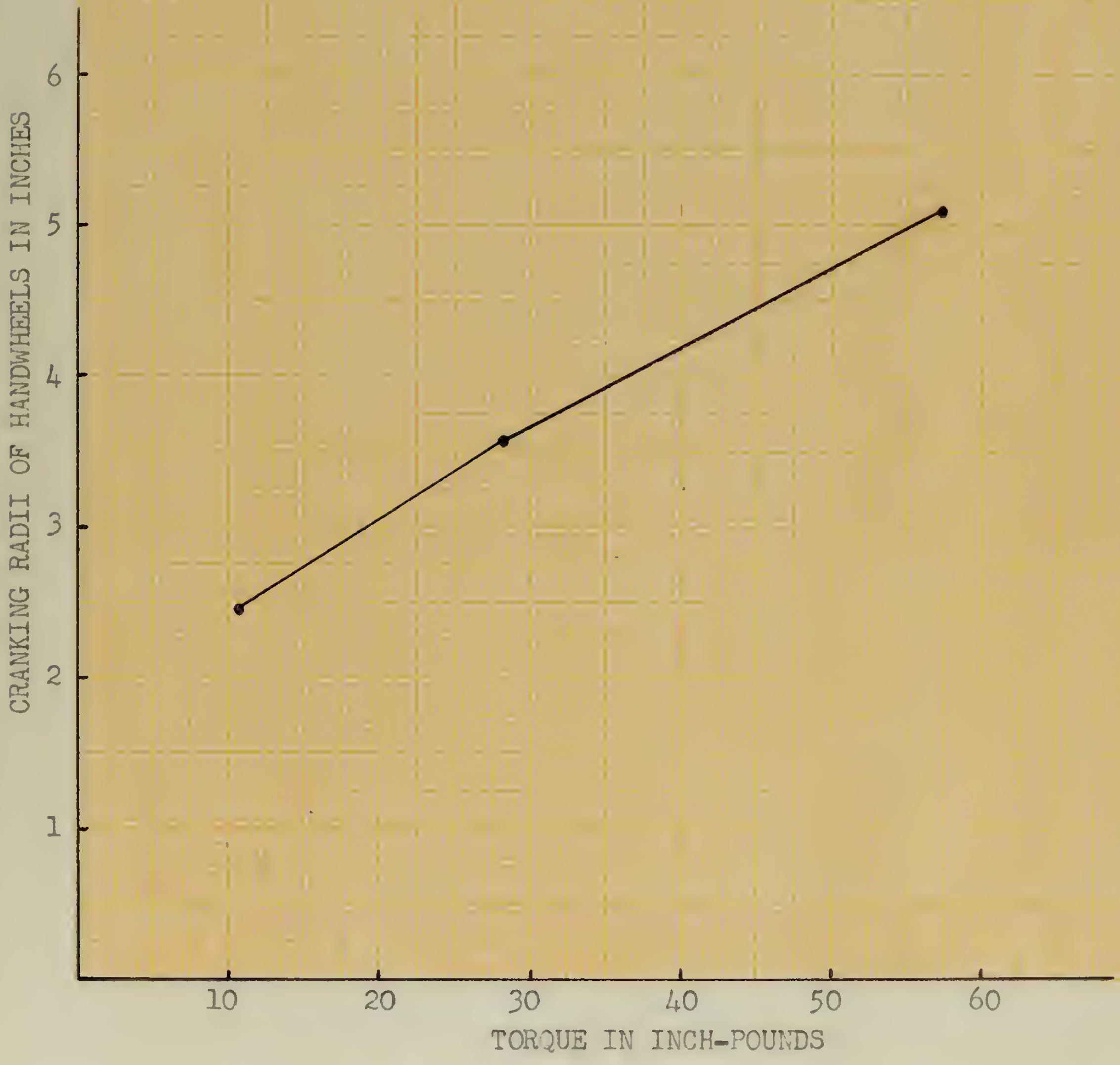


Fig. 4

RELATIONSHIP BETWEEN TORQUES AND CRANKING RADII OF HANDWHEELS FOR THE CONDITION OF MAXIMUM TURNING SPEED



radii of handwheels used in plotting this graph were obtained by minimizing Lagrange's interpolation formula(5) as applied to the curves sketched in Fig. 3. (Refer to Appendix C).

This graph probably provides an approximate solution to the problem of selecting handwheels with a cranking radii ranging from 2.46 to 5.07 inches to operate at maximum speed under a constant torque in the range 10.7 to 57.4 in-lb.

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(5) Scarborough, J. B., Numerical Mathematical Analysis; The John Hopkins Press, 1930, pages 72 and 116.

CONCLUSIONS

1. For each individual the maximum speed of turning seems to be affected, within the range of the present experiment, by two factors:
a) the muscular force required for turning the handwheel, and
b) the radii of the handwheel.

2. There is a strong indication, statistically significant at the 1% level, that, for a given torque, one specific handwheel among those tested produces the maximum turning speed. This fact appears to justify the use of the maximum turning speed as an objective criterion for the selection of handwheels.

3. Within the limits of the torques and handwheel radii indicated, the curve in Fig. 4 should provide an approximate solution for the problem of selecting that handwheel which should allow for the maximum turning speed for a particular torque.

APPENDIX A

DATA FOR ALL OPERATORS, HANDWHEELS AND TORQUES

Table 6. COMPLETE DATA FOR ALL OPERATORS AND HANDWHEELS

TORQUE 0.9 in-lb

Hand-wheels	Operators									
	A	B	C	D	E	F	G	H	I	J
1	34.3	33.6	33.8	40.1	38.0	37.4	37.8	33.8	35.6	35.4
	39.4	33.8	33.5	40.0	33.0	37.8	37.5	35.5	35.1	35.8
	37.5	35.6	34.5	41.0	32.6	36.0	37.8	35.5	36.1	35.6
	35.3	35.8	32.5	37.2	34.8	37.5	37.8	34.2	37.5	33.5
	35.8	33.8	33.8	41.8	36.1	36.0	37.5	35.0	38.0	34.1
	36.0	34.0	32.0	38.6	37.0	37.5	36.6	35.9	35.2	33.3
2	35.5	39.5	34.0	40.0	37.9	39.6	39.5	37.6	37.5	36.0
	36.0	37.5	35.2	40.2	35.5	39.8	39.6	36.4	38.0	37.5
	35.5	36.2	34.3	42.5	35.8	40.0	39.4	38.6	37.5	35.5
	35.8	37.5	33.2	41.0	35.7	39.5	39.6	36.0	39.5	36.0
	37.6	37.5	33.8	40.8	37.5	39.5	39.4	36.3	38.0	37.0
	38.0	37.7	34.0	40.3	37.9	38.1	39.3	36.0	39.5	36.0
3	37.6	39.4	35.6	42.0	37.8	41.2	41.0	37.6	39.6	39.6
	37.5	41.9	37.2	43.0	37.2	40.0	40.4	39.3	37.6	39.3
	39.2	41.5	36.0	43.8	36.5	40.0	41.0	40.0	39.3	38.0
	38.5	43.1	36.0	43.2	37.0	39.9	40.6	39.4	39.5	38.0
	39.5	45.5	37.5	46.0	37.5	41.2	38.5	39.7	37.5	38.0
	39.0	43.3	37.5	44.5	40.0	39.5	41.5	39.4	39.6	38.0
4	46.1	45.7	41.5	45.5	45.5	43.8	43.5	44.0	42.0	45.6
	45.5	43.5	42.0	45.3	47.5	43.6	43.6	45.2	42.0	43.6
	45.0	43.5	41.5	45.5	46.0	41.5	45.3	43.3	43.3	44.0
	45.5	43.8	41.2	47.5	45.3	44.0	43.8	42.0	43.8	45.7
	45.5	43.5	41.6	45.3	47.0	43.8	42.0	45.3	42.2	45.5
	45.7	44.4	41.8	45.8	44.6	43.5	43.6	41.7	43.0	47.0
5	56.6	49.5	45.6	51.5	51.8	48.0	51.8	47.6	47.3	47.8
	56.4	46.0	44.5	51.3	53.8	49.2	51.5	46.1	51.6	47.4
	55.0	50.0	44.6	49.8	52.0	47.8	50.6	47.9	49.9	48.3
	53.5	48.6	45.6	51.2	52.9	47.2	51.8	48.2	47.5	45.0
	55.5	47.3	45.5	51.5	53.5	47.2	51.2	48.8	47.5	48.0
	57.3	49.8	45.8	50.0	53.2	48.6	50.4	48.6	46.0	45.6

Table 7. COMPLETE DATA FOR ALL OPERATORS AND HANDWHEELS

TORQUE 10.7 in-lb

Handwheels	Operators									
	A	B	C	D	E	F	G	H	I	J
1	42.0	45.8	40.0	51.5	45.3	51.2	51.3	45.4	45.7	49.2
	41.5	45.8	37.5	51.5	46.0	51.6	45.5	47.4	47.2	48.1
	42.0	43.6	41.8	53.5	45.4	49.8	50.3	45.3	45.8	49.3
	43.0	45.2	37.8	51.7	48.0	52.4	48.6	45.5	47.3	51.2
	40.0	45.7	41.5	49.5	45.5	51.1	46.3	45.2	45.6	49.9
	43.0	47.5	39.5	51.3	46.0	51.3	52.0	43.7	46.5	51.2
2	39.8	39.1	37.5	43.7	37.8	40.4	44.3	38.5	41.0	41.6
	39.6	38.0	37.1	45.7	37.9	40.6	43.2	39.9	40.0	41.6
	41.5	39.8	39.5	43.8	39.7	39.8	43.3	38.5	41.8	40.8
	41.6	40.8	36.2	46.5	38.2	40.2	43.6	37.6	43.5	41.6
	41.5	40.1	39.0	44.6	38.8	41.0	41.8	38.8	39.6	41.3
	42.0	40.2	37.5	45.5	40.0	38.2	41.5	40.2	42.0	40.5
3	42.0	43.3	39.0	44.8	39.6	41.0	44.0	40.0	42.0	45.0
	41.1	41.9	37.5	43.5	37.9	40.0	44.8	42.0	41.5	43.8
	42.0	41.8	37.8	47.0	40.1	39.4	42.0	42.6	41.8	43.8
	43.5	43.4	37.8	47.5	41.0	41.8	43.2	41.5	41.5	43.5
	40.3	41.8	37.5	45.2	39.5	41.0	42.3	42.2	41.8	43.8
	40.8	43.6	38.0	46.8	41.6	40.2	43.2	40.2	43.1	42.0
4	47.5	45.6	40.0	52.0	44.0	46.5	45.4	45.2	43.7	47.8
	45.4	45.6	43.0	52.2	43.5	46.3	46.0	43.6	44.0	47.2
	45.4	45.1	43.5	55.0	47.3	47.2	43.8	44.8	43.3	47.8
	47.0	44.0	42.5	51.2	45.5	46.6	45.5	43.1	43.5	45.7
	46.4	45.3	41.5	51.4	49.9	46.5	43.8	44.7	42.3	45.3
	48.0	44.2	44.0	53.6	46.5	46.0	43.5	45.8	45.0	45.0
5	55.0	53.6	47.8	60.2	53.6	47.6	53.5	50.2	51.1	54.0
	58.0	53.5	48.4	60.3	53.8	45.9	53.5	51.8	51.5	52.0
	57.5	53.5	48.4	61.8	53.4	48.6	53.5	51.5	51.1	53.1
	57.5	51.6	48.0	57.6	55.6	47.9	54.0	50.5	51.5	53.6
	57.5	53.5	50.0	59.2	55.6	47.6	54.0	51.7	51.5	51.5
	56.0	55.0	51.0	59.8	54.0	45.9	53.4	50.3	51.3	51.6

Table 8. COMPLETE DATA FOR ALL OPERATORS AND HANDWHEELS

TORQUE 28.2 in-lb

Hand-wheels	Operators									
	A	B	C	D	E	F	G	H	I	J
1	57.0	79.6	56.5	81.3	59.6	89.0	75.0	63.8	75.1	64.0
	57.5	81.7	53.0	77.6	59.1	79.5	77.3	65.0	75.2	65.0
	54.0	84.5	55.5	79.3	59.5	81.3	77.8	62.0	77.5	63.6
	55.0	79.6	54.0	80.4	59.8	83.3	81.0	63.2	77.2	63.7
	59.7	83.2	56.2	78.3	60.4	81.5	77.5	60.8	77.5	65.3
	57.3	79.6	52.2	77.2	58.4	77.5	75.0	63.2	73.2	63.8
	44.0	64.0	47.0	60.0	44.0	65.3	57.6	51.3	63.1	53.5
	47.5	61.5	48.5	63.5	47.2	59.8	58.0	50.0	61.5	55.6
	46.8	61.3	46.0	63.0	53.5	67.5	58.6	53.0	63.9	53.2
	47.0	64.0	49.5	59.9	52.0	63.5	57.3	53.8	63.2	55.7
	45.3	59.3	47.5	63.3	45.3	69.4	57.6	51.2	61.5	52.8
	45.4	63.5	47.5	65.2	51.6	63.5	55.0	55.8	61.3	54.5
3	45.5	51.3	42.6	50.0	46.4	45.8	45.0	43.3	43.5	45.3
	47.5	49.9	42.5	49.5	44.3	47.5	45.5	43.7	43.5	43.3
	43.5	51.5	42.0	49.5	47.1	47.5	47.4	42.8	43.5	43.0
	45.5	51.8	41.8	51.5	45.0	45.5	45.6	43.2	43.6	44.0
	47.4	51.8	43.6	51.2	47.8	47.5	47.5	44.8	43.8	44.7
	44.4	53.0	41.5	51.9	48.2	47.5	47.5	44.0	43.7	45.3
4	49.5	51.3	45.5	53.8	49.6	49.6	47.5	45.5	46.4	49.2
	48.9	52.3	43.8	49.0	47.6	50.5	47.5	45.6	45.3	47.8
	48.2	50.5	45.4	52.0	47.5	50.6	49.6	45.8	45.7	47.8
	49.6	55.1	43.3	54.3	47.5	50.0	48.0	45.4	46.7	49.4
	49.3	54.2	45.7	50.4	47.9	50.0	47.3	45.8	46.8	49.5
	49.8	52.1	44.0	50.5	50.0	49.5	47.8	45.9	46.7	47.5
5	58.2	60.0	49.5	53.0	55.2	51.6	55.6	53.5	57.3	55.5
	56.8	61.4	49.5	53.4	57.0	53.5	53.2	53.5	55.6	55.1
	55.5	59.7	48.0	55.7	54.4	50.5	53.3	51.8	55.4	54.0
	57.9	60.0	49.2	54.0	54.9	51.0	54.3	52.8	58.0	54.6
	57.5	59.2	51.5	55.0	59.1	51.5	54.6	52.0	59.1	54.8
	58.0	62.0	49.8	55.6	57.0	51.3	53.2	51.3	55.3	55.3

Table 9. COMPLETE DATA FOR ALL OPERATORS AND HANDWHEELS

TORQUE 57.4 in-lb

Handwheels	Operators									
	A	B	C	D	E	F	G	H	I	J
1										
2										
3	61.4	67.8	52.0	67.2	61.3	75.2	65.0	55.8	67.2	61.5
	60.8	69.5	49.3	67.3	59.6	75.5	64.5	59.5	66.0	63.6
	56.8	69.6	51.8	69.0	63.1	74.5	62.6	55.6	69.0	63.5
	59.3	73.2	50.0	67.7	65.4	79.0	66.2	57.5	69.3	63.5
	62.0	81.3	53.5	65.3	63.5	77.0	64.2	55.5	65.4	65.2
	57.5	81.0	52.0	69.5	63.6	76.4	66.0	55.5	66.0	65.5
4	52.5	61.0	49.6	52.6	53.6	51.8	55.6	51.6	53.5	53.0
	52.8	59.2	47.8	52.3	55.5	53.2	57.2	50.2	57.5	51.5
	53.0	58.8	49.5	52.8	53.0	52.6	54.4	52.5	57.2	52.3
	54.3	61.0	50.0	51.3	54.0	52.6	56.5	51.6	55.5	53.2
	54.0	61.6	49.6	53.7	55.2	53.0	56.5	52.4	55.0	51.8
	50.0	61.4	49.5	52.0	55.8	51.5	56.8	52.0	55.0	52.5
5	57.2	59.4	51.3	58.6	59.2	59.5	61.8	57.3	61.4	56.0
	55.5	61.8	50.5	58.3	59.7	57.3	60.6	55.5	61.2	57.2
	58.2	61.5	50.9	59.6	57.7	55.5	59.3	55.3	61.4	53.5
	61.0	63.4	52.0	61.0	59.5	56.0	59.3	55.6	62.3	55.0
	57.3	65.5	51.5	59.3	59.5	55.5	58.4	55.7	62.7	56.0
	58.0	63.9	51.6	61.3	59.2	53.3	59.3	55.2	63.1	57.0

Table 10. COMPLETE DATA FOR ALL OPERATORS AND HANDWHEELS

TORQUE 84.6 in-lb

Hand-wheels	Operators									
	A	B	C	D	E	F	G	H	I	J
1										
2										
3										
4	63.4	65.1	51.5	72.8	62.8	71.5	65.2	61.4	69.3	61.5
	63.6	73.5	53.8	73.5	63.4	71.5	64.5	61.5	71.5	61.4
	61.8	69.3	53.5	69.6	65.3	69.6	65.5	61.2	69.4	61.6
	64.6	73.1	52.3	73.0	62.0	69.5	65.5	61.9	69.7	59.9
	64.2	66.5	54.9	69.6	61.2	71.5	66.2	61.8	71.1	59.7
	67.0	70.8	53.5	75.5	61.2	71.5	66.7	59.3	70.0	61.0
5	61.6	65.4	51.5	61.1	61.3	71.7	63.4	58.8	65.2	61.6
	63.3	67.5	50.5	59.6	59.5	69.2	62.0	59.0	63.3	61.5
	63.3	62.3	50.5	59.5	61.3	67.5	62.8	57.2	65.8	59.3
	61.2	65.3	53.5	61.6	65.5	67.8	62.2	57.9	65.0	59.5
	61.5	67.0	52.0	59.2	61.5	69.5	62.5	57.5	64.2	59.7
	59.8	67.3	53.8	61.3	63.5	67.5	61.5	58.0	65.0	57.5

APPENDIX B

STATISTICAL ANALYSIS OF RESULTS

The Homogeneity of Measurement Error

To find out whether we have homogeneity of measurement error we take the range R, for each cell, and then we calculate $\bar{R}$, i.e., the mean range for all cells. Then we can set the Upper Control Limit for ranges in samples of six observations:(6)

$$UCL_R = D_4\bar{R} = 2.00\ \bar{R} = 6.281$$

We want or hope that a not excessive number of the 200 R's is above the UCL_R. If so, then, we have homogeneity of measurement error.

As can be seen from Tables 1 to 5, five points are above the UCL. The probabilities of a point being above and below the UCL are:

P(a point above UCL) = 0.004 approximately (7)

P(a point below UCL) = 0.996 approximately

Then, in 200 samples we expect 200 x 0.004 = 0.8 above the UCL. Observation of the data discloses five above, which raises the question as to whether this is excessive.

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(6) Grant, E. L., Statistical Quality Control; McGraw Hill, 1949, p. 537.

(7) Pearson, E. S., The Percentage Limits for the Distribution of Range in Samples from a Normal Population, Biometrika, v24, p404, November 1932.

The binomial could be used to find the probability of five points or more to be above the UCL, or we can use the Poisson as an approximation.(8)

In our case we have:

$$np' = 200 \times 0.004 = 0.8$$

$$P(4 \text{ or less}, np' = 0.8) = 0.999$$

$$P(5 \text{ or more}, np' = 0.8) = 0.001$$

This is significantly rare and indicates some definite tendency to non-homogeneity.

This tendency to non-homogeneity is a definite one, but not very strong. So we will continue to use $\bar{\bar{X}}$ but we should be somewhat more conservative in our interpretations because of this.

Significance test for the speed of handwheels

To test, for example, whether handwheel n$^{\underline{o}}$2 or n$^{\underline{o}}$3 gives lower times (or higher speeds) for a 10.7 in-lb torque we find $\bar{\bar{X}}_2$ = mean time for all observations made on handwheel n$^{\underline{o}}$2 for the torque under consideration. This is to be compared to that for handwheel n$^{\underline{o}}$3.

We make the test by using an estimated σ'_x, i.e., the population standard deviation for within cell variation. For samples of size 6 we have:(9)

---

(8) Grant, E. L., ibid., p542.

(9) Grant, E. L., op. cit., p635.

$$\sigma'_x = \frac{\bar{R}}{d_2} = \frac{3.1405}{2.534} = 1.241$$

$$t = \frac{\bar{X}_2 - \bar{X}_3}{\sigma'_x\sqrt{\frac{1}{60} + \frac{1}{60}}} = \frac{1.21}{0.2264} = 5.34$$

If t is larger than 2.58,(10) in size, then we have observed a t which by chance alone would occur less often than one time in 100 and the difference between the means of the observations made on handwheels 2 and 3 is significant at the 1% level.

As can be seen from the curves in Fig. 3, the difference just tested is about the smallest. So it seems to be hardly necessary to apply the t test to any other pair of handwheels.

---

(10) Tippett, L. C. H., Technological Applications of Statistics; John Wiley & Sons, 1950, page 8.

APPENDIX C

Estimation of the minimum time per revolution using Lagrange's interpolation formula

a) Torque: 57.4 in-lb

Observed points:

Cranking radii	Average time per revolution
$x_o = 3.062$	$y_o = 64.38$
$x_1 = 4.500$	$y_1 = 53.77$
$x_2 = 6.375$	$y_2 = 58.04$

Lagrange's interpolation formula:(11)

$$f(x) = A_o(x-x_1)(x-x_2)+ A_1(x-x_o)(x-x_2)+ A_2(x-x_o)(x-x_1)$$

where:

$$A_o = \frac{y_o}{(x_o-x_1)(x_o-x_2)}$$

$$A_1 = \frac{y_o}{(x_1-x_o)(x_1-x_2)}$$

$$A_2 = \frac{y_2}{(x_2-x_o)(x_2-x_1)}$$

After substituting the numerical values and rearranging the terms we obtain:

---

(11) Scarborough, J. B. op.cit.

$$f(x) = 2.95\ x^2 - 29.9\ x + 128.9$$

This function has a minimum at $x = 5.07$, as is obtained by differentiating and setting the derivative equal to zero.

b) Torque: 28.2 in-lb

Observed points:

Cranking radii	Average time per revolution
$x_o = 1.625$	$y_o = 69.44$
$x_1 = 2.250$	$y_1 = 55.89$
$x_2 = 3.062$	$y_2 = 46.14$
$x_3 = 4.500$	$y_3 = 48.50$
$x_4 = 6.375$	$y_4 = 54.69$

Following the procedure outlined in the preceeding page we find:

$$f(x) = -0.2353x^4 + 2.4598^3 - 2.6622x^2 - 32.2823x + 120.0109$$

This function has a minimum at $x = 3.576$.

c) Torque: 10.7 in-lb

Observed points:

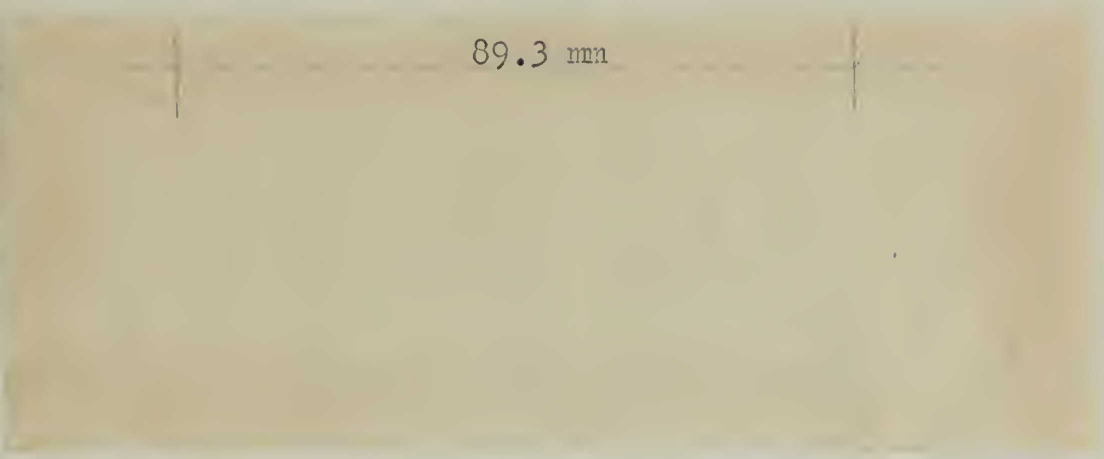
Cranking radii	Average time per revolution
$x_o = 1.625$	$y_o = 46.61$
$x_1 = 2.250$	$y_1 = 40.66$
$x_2 = 3.062$	$y_2 = 41.87$
$x_3 = 4.500$	$y_3 = 45.85$
$x_4 = 6.375$	$y_4 = 54.17$

For this data we get:

$$f(x) = 0.5059x^4 - 8.2540x^3 + 48.4284x^2 - 118.5221x + 143.2163.$$

This function has a minimum at $x = 2.458$.

APPENDIX D



SAMPLE OF KYMOGRAPH PAPER

APPENDIX E

Table 11

PHYSICAL CHARACTERISTICS OF OPERATORS

OPERATOR	AGE (years)	HEIGHT (ft-in)	WEIGHT (pounds)	ELBOW HEIGHT (inches)
A	31	5 - 7	170	42
B	31	5 - 7	155	42
C	35	5 -11	165	44 1/2
D	32	6 - 2	210	46
E	28	6 - 0	190	46
F	39	5 -10	175	44 1/2
G	31	5 - 7	160	42
H	34	6 - 0	205	44
I	29	6 - 0	190	44
J	29	5 - 8	164	40 1/2

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